Hadron Production at Intermediate p_T at RHIC

Tatsuya Chujo § **for the PHENIX Collaboration**‖

Vanderbilt University, Nashville, TN 37235, USA

Abstract. Large proton and antiproton enhancement with respect to pions has been observed at intermediate transverse momentum $p_T \approx$ 2-5 GeV/c in Au+Au collisions at RHIC. To investigate the possible source of this anomaly, the production of ϕ mesons and two particle angular correlations triggered by mid-p_T baryons or mesons are studied. We also present the first measurement of proton and antiproton production at $\sqrt{s_{NN}} = 62.4$ GeV in Au+Au collisions, which aims to study the energy dependence of the observed baryon enhancement.

1. Introduction – Baryon Anomaly at RHIC

One of the most striking observations in the central heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) is a large enhancement of baryons and antibaryons relative to pions at intermediate $p_T \approx$ 2–5 GeV/c [1, 2], while the neutral pions [3] and inclusive charged hadrons [4] are strongly suppressed at those p_T. The (anti)proton to pion ratio is enhanced by almost a factor of three when one compares peripheral reactions to the most central Au+Au reactions. In this region of p_T fragmentation dominates the particle production in pp collisions. It is expected that fragmentation is independent of the colliding system - hence the large baryon fraction observed at RHIC comes as a surprise.

Large proton to pion ratios have also been observed in heavy ion collisions at the AGS and SPS. However, the large net baryon density at these energies indicates that most of the protons come from the initial state of the reaction. The anti-proton yields at the SPS and AGS are one and three orders of magnitude, respectively, below the production at RHIC. We note that the SPS data does not extend above $p_T > 2$ GeV/c, but the overall lower production of anti-protons makes it unlikely that anti-proton excesss above the fragmentation values is present.

At RHIC energies, most of protons are produced in the reaction rather than transported from the beam. Both proton and anti-proton yields are enhanced with respect to the pion yields. Most often the observed enhancement is interpreted as a consequence of a strong radial flow which pushes the heavier particles to larger p_T. In this paper we address two outstanding questions: (1) whether the anomalous baryon
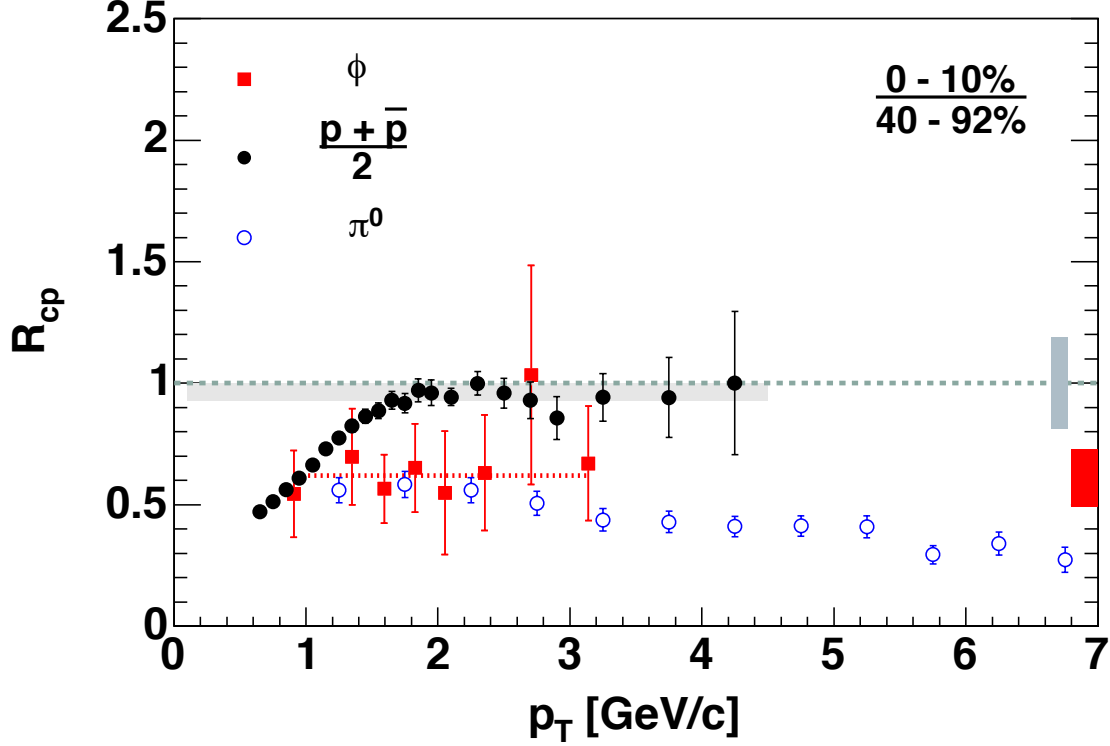
Figure 1. The R_{CP} of the ϕ mesons as measured in the K^+K^- channel [6, 7], compared to the protons, antiprotons, and π^0 for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

enhancement at RHIC is a mass effect, or a baryon/meson effect. (2) what fraction of the baryons at intermediate p_T originate in the fragmentation. The PHENIX experiment measured ϕ meson production and jet correlations with identified particle trigger with the goal to solve the baryon puzzle at RHIC. We also include results from $\sqrt{s_{NN}} = 62.4$ GeV Au+Au collisions, which will help to understand the energy dependence of the observed phenomena.

2. Production of ϕ mesons

The ϕ meson is an ideal test particle for investigating if the observed baryon anomaly is cased by just the strong radial flow (mass effect) or not, since ϕ is a heavy meson that has mass similar to the mass of the proton. Figure 1 shows R_{CP}, the ratio of the yields in central to peripheral Au+Au collisions scaled by binary collisions, for protons, pions and ϕ mesons. The ϕ is detected via its KK decay channel [5, 6, 7, 8]. The ϕ follows the suppression pattern of the pions within errors, indicating that the observed behavior of the protons is not characterized by their mass, but rather - by the number of valence quarks (meson or baryon). The clear baryon and meson effect at intermediate p_T has also been observed by the STAR experiment in R_{CP} of K^*, K_s^0, Λ, and Ξ [9, 10].

In the hydrodynamical model with the jet fragmentation [11], it is found that there is a general agreement in p/π and $\bar{p}/\pi$ ratios between data and the model. But it might be challenging for the model to reproduce the suppression pattern on ϕ and K^* by the hydrodynamical framework, since the heavier particle should gain a similar p_T boost by the strong hadronic flow, regardless whether they are baryons or mesons. On the other hand, the recombination models [12, 13, 14] give a more natural explanation on the baryon/meson effect, since the essential ingredient of this model is the number of quarks in a hadron.

3. Jet correlations

A crucial test of the origin for the baryon enhancement is to see if baryons in the intermediate p_T exhibit a characteristic correlation of jets from hard-scattered partons. We have measured two particle correlations where the trigger particle is an identified meson (π, K) or baryon (p, $\bar{p}$) at $2.5 < p_T < 4.0$ GeV/c [15]. Associated particles, i.e. lower p_T charged hadrons, near in azimuthal angle to the trigger are counted (conditional yield per trigger).

Figure 2 shows the $\Delta\phi$ distributions with trigger mesons (left) and baryons (right) measured at midrapidity in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The jet-like correlations are clearly seen over the combinatorial background, particularly at small relative angle inside the expected jet cone. Figure 3 shows the conditional yield per trigger of partner particles in p+p, d+Au, and Au+Au collisions, as a function of centrality. The top panel shows partner yield at small relative angle, from the same jet as the trigger hadron. We observe an increase in partner yields in mid-central Au+Au compared to the d+Au and p+p collisions. In Au+Au collisions, the near side yield per *meson* trigger remains constant as a function of centrality, whereas the near-side yield per *baryon* trigger decreases in the most central collisions as expected if a fraction of the baryons were produced by soft processes such as recombination of thermal quarks. The dashed line in Figure 3 represents an upper limit to the centrality dependence of the jet partner yield from thermal recombination. The data clearly disagree with both the centrality dependence and the absolute yields of this estimation, indicating that the baryon excess has the same jet-like origin as the mesons, except perhaps in the highest centrality bin. The bottom panel of Figure 3 shows the conditional yield of partners on the away side. It drops equally for both trigger baryons and mesons going from p+p and d+Au to central Au+Au, in agreement with the observed disappearance [16] and/or broadening of the dijet azimuthal correlations. It further supports the conclusion that the baryons originate from the same jet-like mechanism as mesons.

Recently several version of recombination models have been proposed, e.g. a purely thermalized quark recombination [12], the model including shower partons or hard partons with thermal partons [13, 14]. Figure 4 shows those recombination model calculations compared to the p/π ratio from PHENIX (the figure taken from Ref. [8]). All models are able to reproduce the general features of data at $p_T > 3$ GeV/c. By
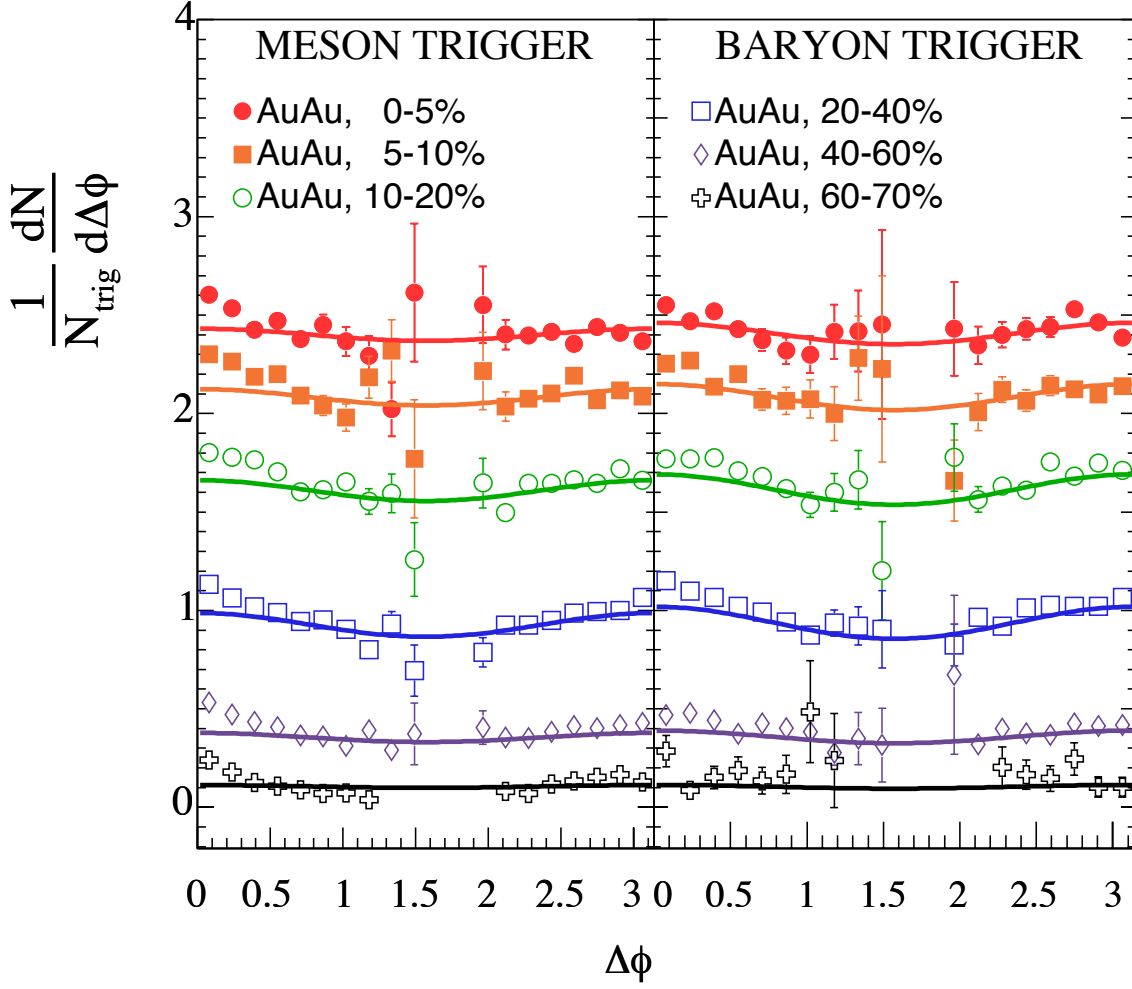
Figure 2. $\Delta\phi$ distributions for meson (left) and baryon (right) triggers with $2.5 < p_T < 4.0$ GeV/c and associated charged hadrons with $1.7 < p_T < 2.5$ GeV/c for six centralities in Au+Au collisions [15]. The solid lines indicate the calculated combinatorial background in the event modulated by the measured elliptic flow.

including the hard-thermal component in the model, it seems there is a better agreement with the data, which is consistent with results of two particle jet correlations as shown above. It should be noted that the simple picture of recombination of purely thermal quarks [12] may apply, since the conditional yield with near-side baryons in most central collisions appears to decrease.

4. p/π and $\bar{p}/\pi$ ratios at $\sqrt{s_{NN}} = 62.4$ GeV

To study the excitation function of hadron production at the beam energy between CERN-SPS ($\sqrt{s_{NN}} = 17.3$ GeV) and RHIC, the data in $\sqrt{s_{NN}} = 62.4$ GeV in Au+Au was taken as a part of Run-4 RHIC program in 2004. This lower energy data provides an important information on the baryon production and transport at mid-rapidity between SPS and RHIC. Figure 5 shows the p/π^+ and $\bar{p}/\pi^-$ ratios for central (0–10%), and non-
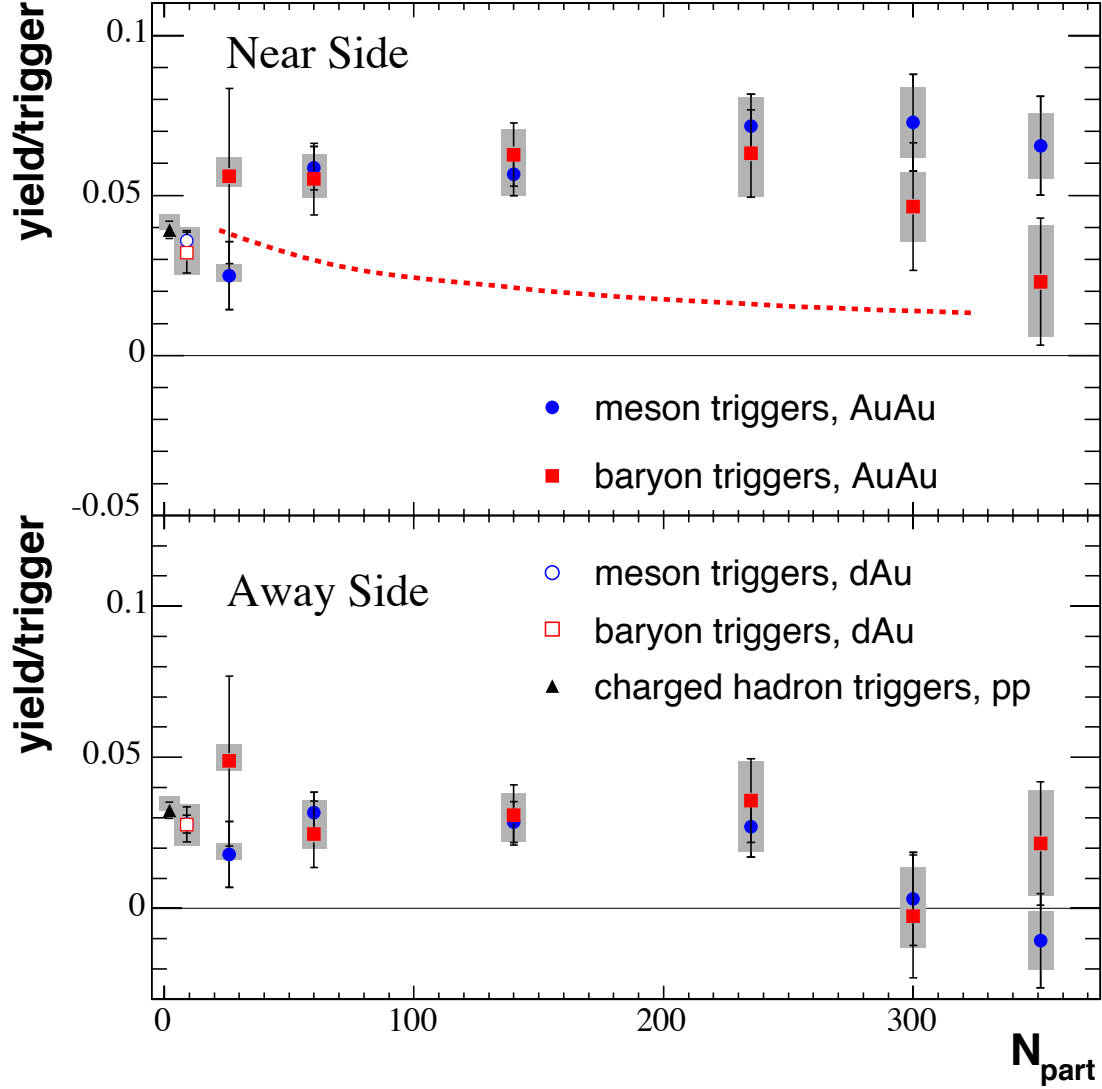
Figure 3. Yield per trigger for associated charged hadrons between $1.7 < p_T < 2.5$ GeV/c for the near- (top) and away- (bottom) side jets [15]. The dashed line (top) represents an upper limit of the centrality dependence of the near-side partner yield from thermal recombination.

central (30–60%) Au+Au collisons at $\sqrt{s_{NN}} = 62.4$ GeV. It should be noted that the feed-down corrections from weak decays are not yet applied to these results. The data shows a similar large proton contribution at intermediate p_T as seen in 130/200 GeV Au+Au, while there is a less antiproton contribution compared to the 200 GeV results. Proton-antiproton pair production is reduced, and the baryon chemical potential is larger at 62.4 GeV than that of 200 GeV in Au+Au collisions.
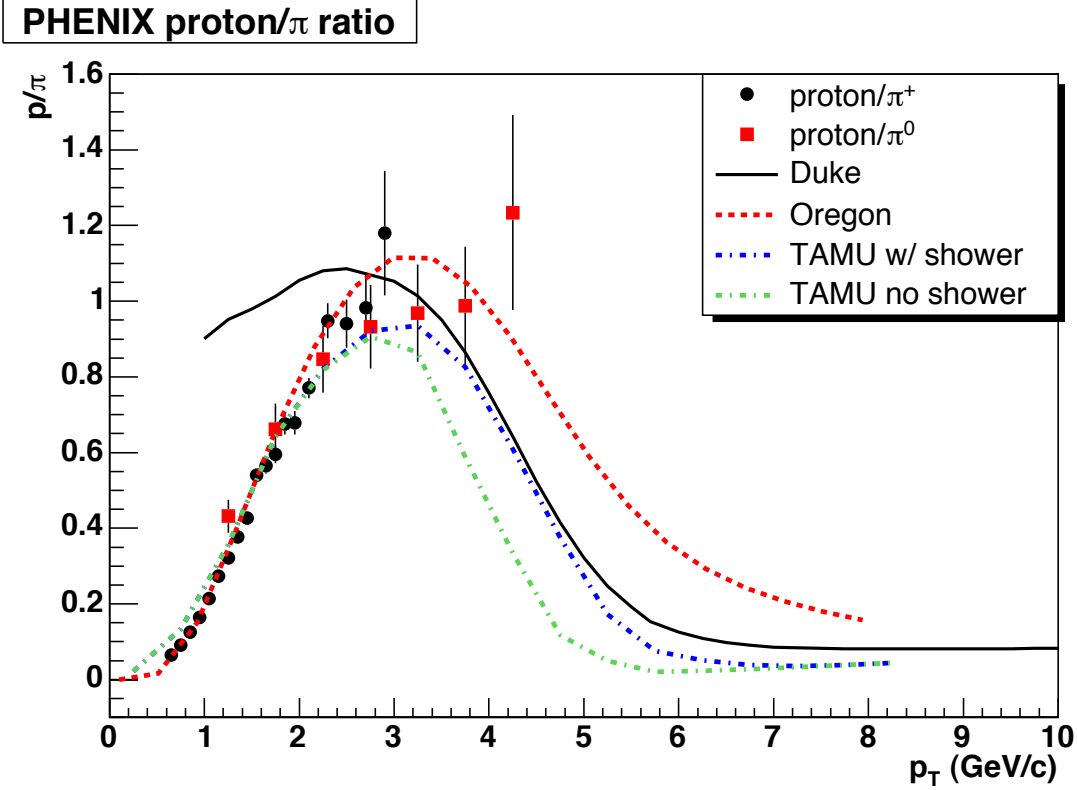
Figure 4. The proton to pion ratio measured by PHENIX for Au+Au collisions at $\sqrt{s_{NN}} = 200$GeV with several comparisons to recombination models. The figure taken from [8].

5. Summary

We presented the results on the production of ϕ mesons and two-particle azimuthal angular correlations with both the intermediate p_T baryon and meson trigger in Au+Au collisions at RHIC. The R_{CP} of ϕ follows the suppression pattern of π^0's, which indicates that the baryon enhancement at intermediate p_T in central Au+Au is not related to the paticle mass, but rather - to the number of valence quarks in the hadron. In the correlations study using identified particle trigger, the result shows that a large fraction of the baryons produced at intermediate p_T in Au+Au collisions originate from jet fragmentation, perhaps except for the most central reactions. The recombination models which include hard-thermal component are in better agreement with the data than models that treat recombination of thermal quarks only. The first measurements of p/π^+ and $\bar{p}/\pi^-$ ratios at $\sqrt{s_{NN}} = 62.4$ GeV in Au+Au collisions are studied. The data indicates a proton-antiproton pair production is reduced, and the baryon chemical potential is larger at 62.4 GeV than that of 200 GeV in Au+Au collisions.

References

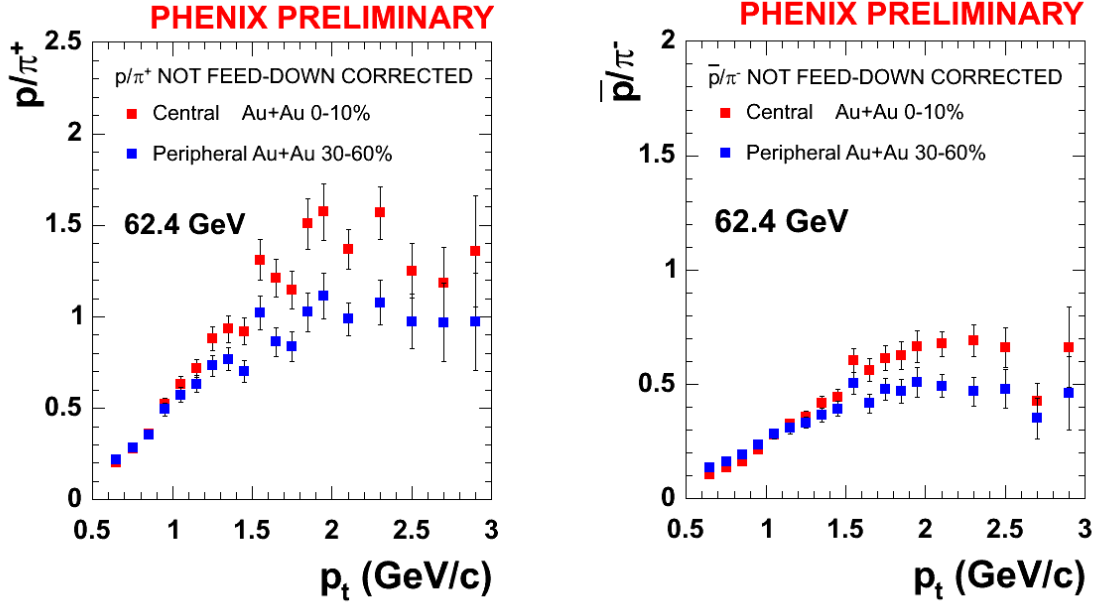[1] PHENIX Collaboration, S. S. Adler *et al.*, *Phys. Rev. Lett.* **91**, 172301 (2003).

Figure 5. p/π^+ (left) and $\bar{p}/\pi^-$ (right) ratios for central (0-10%), and non-central (30-60%) Au+Au collisons at $\sqrt{s_{NN}} = 62.4$ GeV. Note that the feed-down corrections from weak decays are not corrected.

[2] PHENIX Collaboration, S. S. Adler *et al.*, Phys. Rev. C **69**, 034909 (2004).

[3] PHENIX Collaboration, S. S. Adler *et al.*, *Phys. Rev. Lett.* **91**, 072301 (2003).

[4] PHENIX Collaboration, S. S. Adler *et al.*, Phys. Rev. C **69**, 034910 (2004).

[5] J. Velkovska, J. Phys. **G 30**, S835-S844 (2004), nucl-ex/0405013

[6] PHENIX Collaboration, S. S. Adler *et al.*, nucl-ex/0410012, to appear in Phys. Rev. C **.**

[7] D. Mukhopadhyay (these proceedings); D. Pal (these proceedings).

[8] PHENIX Collaboration, K. Adcox *et al.*, to appear in Nucl. Phys. A **,** nucl-ex/0410003.

[9] STAR Collaboration, J. Adams *et al.*, *Phys. Rev. Lett.* **92**, 052302 (2004).

[10] STAR Collaboration, M. A. C Lamont, *J. Phys. G: Nucl. Phys.* **30**, S963 (2004).

[11] T. Hirano, Y. Nara, Phys. Rev. C **69**, 034908 (2004).

[12] R. J. Fries, B. Muller, C. Nonaka, S. A. Bass, *Phys. Rev. Lett.* **90**, 202303 (2003); R. J. Fries, B. Muller, C. Nonaka, S. A. Bass, Phys. Rev. C **68**, 044902 (2003);

[13] R. C. Hwa, C. B. Yong, Phys. Rev. C **67**, 034902 (2003); R. C. Hwa, C. B. Yong, nucl-th/0401001.

[14] V. Greco, C. M. Ko, P. Levai, *Phys. Rev. Lett.* **90**, 202302 (2003);

[15] PHENIX Collaboration, S. S. Adler *et al.*, submitted to *Phys. Rev. Lett.* **,** nucl-ex/0408007.

[16] STAR Collaboration, C. Adler *et al.*, *Phys. Rev. Lett.* **90**, 082302 (2003).